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ACCURATE VELOCITY MEASUREMENT WITH A NARROWBAND DOPPLER CURRENT PROFILER

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Abstract

Accurate velocity of an ocean going vessel with respect to the water can be determined in real time by utilizing a Doppler Current Profiler(DCP) system. The DCP employs multiple sonar beams with a plurality of bins or returns from various depth segments. These returns are then statistically processed to attain stable and accurate velocity information. The process is performed without any temporal averaging allowing it to be employed where raw data requirements must be met such as the damping of inertial navigation systems.

Introduction

There exists an ongoing effort to improve the navigation capabilities of US Navy survey vessels. One particular effort has been focused on improving the performance of the inertial navigation system used by these vessels by improving the external damping velocity supplied to the system. A simultaneous but previously unrelated project introduced an ocean current measuring device called a Doppler Current Profiler(DCP) onto these survey vessels. Once the initial DCP data was collected and analyzed it was realized that the DCP had the potential to provide an improved damping velocity source to the inertial navigator.

Additional data collected aboard US Navy survey and test vessels have been analyzed and compared to other velocity and navigation sensors and used to develop an error model of the DCP itself. The results indicate that the DCP can provide a more stable and accurate velocity than conventional velocity logs. The US Navy patented technique (Ref. 1) of using a DCP as a velocity log device is referred to as Doppler Velocity Profiling.

There is presently a new generation Broadband Acoustic Doppler Current Profiler being introduced with improved accuracy over the existing narrowband DCP. This can only improve the performance of the DCP as both an ocean current measuring device and a ship's velocity log.

VELOCITY PROFILE DEVELOPMENT HISTORY

US Navy ships and submarines utilize an Integrated Navigation System that consists of radio, satellite and inertial navigation sensors. The inertial navigator is subject to Schuler oscillation errors that can be caused by external disturbances such as gravity anomalies. In order to recover from or damp out these oscillation errors an external velocity input is used. The most common input is a single Electromagnetic Log (EMlog).

The EMlog consists of a main electronics unit that displays and outputs its measured velocity and a sword that is lowered into the water via a sea valve in the ship's hull. The sword has sensors on it that generate an electric current proportional to the speed at which it is moved through the water. The EMlog is capable of measuring the velocity in the fore/aft (V_f/a) direction. A problem with the EMlog is that it randomly goes out of calibration and provides inconsistent and biased velocities. The fact that the EMlog goes out of calibration and that it also is a water referenced velocity introduces two additional external disturbance sources. Course changes when EMlog calibration errors are present and changing ocean currents will excite Schuler oscillations.

In an attempt to provide a more stable damping velocity source for the inertial navigator US Navy survey ships calculate a velocity derived from two EMlogs and one Doppler Sonar Velocity Log (DSVL).

The typical DSVL is a two or four beam Doppler sonar based system that consists of a main electronics unit, a transmitting section, a transducer and a display unit. The DSVL measures Velocity fore/aft (V_f/a) and Velocity port/starboard (V_p/s). The DSVL has fixed operating parameters and takes its sample from a section of water within a few meters of the ship's hull. The DSVL does not normally require calibration. The display is generally the target output of the DSVL, but a digital output can be obtained by tapping off the interface between the main electronics unit and the display unit. Since the system is designed to supply velocity to the highly filtered display the raw velocity data tends to be noisy and full of spurious points or outliers. (See figure 1)

A common problem that both the EMlog and the DSVL share is that they both measure the ship velocity over the water in an area that is heavily influenced by water that is displaced by the ship's hull. The depths to which this displaced water reaches varies with each ship and to a lesser extent the speed at which it is traveling. The ships that were used in the collection of the data used in this report ranged in size from 250' to 600' with normal operating speeds that ranged from 4 knots to 21 knots, although data were collected at speeds as low as 0 knots. (See Figure 2) The water displaced by the hull or these ships routinely reached depths of 20 to 25 meters. (See figure 2) The area of measurement used by both the EMlog and the DSVL are

within this range. This indicates that even though the method of using two EMlogs and a DSVL may be superior to using a single EMlog for calculating a damping velocity, there is room for improvement.

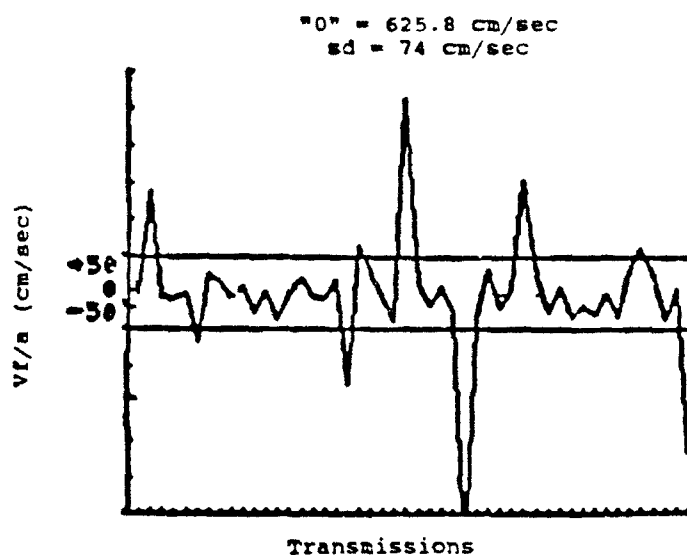


Figure 1) Plot of velocity fore/aft as measured by a standard technology DSVL. (Ref. 2)

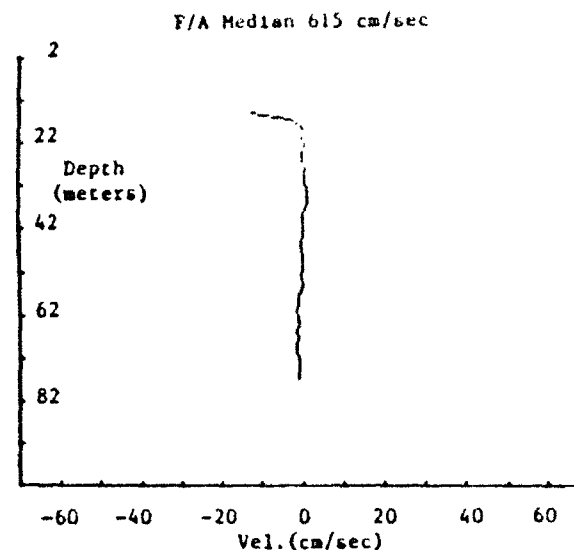


Figure 2) Characteristic profile of water displaced by a ship's hull. (Ref. 3)

A technology that has emerged from the DSVL is Doppler Current Profiling. The Doppler Current Profiler (DCP) is also a Doppler sonar based system, but both its transmitting and receiving sections are software controllable and much more sophisticated than that of the DSVL. With the DCP up to 128 samples or depth bins per beam can be measured from a single transmission. This allows for statistical processing of velocities without any temporal averaging thus providing instantaneous velocities for inertial navigator damping (Ref. 1) that are free from the calibration errors and spurious data points that are characteristic of the EMlog or DSVL. As its name implies the DCP is primarily used for measuring ocean current profiles. With the proper software the DCP can simultaneously collect current profile data and output accurate velocities for inertial navigator damping. The type of DCP system used for the collection of most of the current profile data analyzed in this study was an RD Instruments 115 kilohertz(khz) vessel mounted DCP. The transmitting and receiving sections are both contained in a single main electronics housing and are controlled via either a serial or parallel link to an IBM PC compatible computer. The transducer of the system is configured as a four beam concave unit with an output of 130 Watts per beam. The 115 khz system is not a commercially available off the shelf unit.

It is a modified version of the 150 khz system. This modification was performed to meet other requirements of the vessels on which the systems were installed. The measurement accuracy is slightly compromised by altering the transmit frequency but the profile depth range is increased. The increased profiling range is due to the decrease of acoustic absorption that comes with the lower frequency. The tradeoff between measurement resolution and profiling range is the prime consideration when selecting the frequency of a DCP for an application. Another factor to take into account when selecting a DCP system is that the lower the transmit frequency, the larger the transducer and associated sea chest.

Typical vessel mount profiling ranges for the high powered commercially available systems and the 115 khz system are as seen in table 1.

Table 1.

OPERATING FREQUENCY	PROFILING RANGE
75 khz	700 meters
115 khz	450 meters
150 khz	350 meters
300 khz	200 meters
600 khz	100 meters
1200 khz	30 meters

Another factor that greatly influences the profiling range of a DCP is the characteristic scatterers in an area. The scatterers are primarily made up of plankton and other small particles that are suspended in the water and provide backscattering targets to reflect the sound back to the transducer. These scatterers move with the water and provide an excellent reference for measuring water movement. In some areas these scatterers are not prevalent at the deeper depths and this reduces the profiling range of a given system. An example of such an area is off the Atlantic coast of Florida where systems that normally achieve water track profiles of 400 to 500 meters are only able to profile to 250 meters.

When the application is ship velocity measurement, 250 meters is more than adequate.

Through the use of the DCP and the velocity profiling technique several improvements can be made over the traditional velocity logging methods. The single ping DCP data does not contain the high number of spurious points that the traditional log data contains. The DCP is less affected by bias than the other logs. The DCP is not affected by the hull displaced water or the wind driven currents because the DCP reference layer is movable. The DCP provides three axes of velocity measurement and a bottom track capability when in the proper depth range. The DCP has self checking of validity through error velocity calculations and signal-to-noise ratio checks.

THE VELOCITY PROFILE ALGORITHM

The DCP has software selectable operating parameters, this allows for a flexibility in the manner the data is collected and processed. Two very conspicuous parameters when using the DCP as a velocity profiling device are the number of depth bins collected and the size of each of these bins. The number of depth bins collected can be from 1 to 128 and the range of the depth bin size is from 1 meter to 32 meters. The manufacturer recommends to keep the transmitted pulse length and the depth bin size equal to achieve optimal system performance. The manufacturer's recommended parameters for optimal current profiling with the 115 khz DCP is 64 bins, 8 meter bin size and 8 meter transmit pulse. Shipboard empirical testing verified these values. Since the DCP systems of the US Navy survey vessels are for both current profiling and velocity profiling simultaneously these parameters are used for most of the velocity profile testing.

The current profile and velocity profile data are both calculated from the data set returned from the same transmission. This data is sent to the processing computer by the DCP main electronics unit (MEU) in a radial velocity format. The radial velocities represent the Doppler shift measured for each bin of each beam. The total number of radial velocity values is the product of the number of beams and the number of bins selected. The velocity values are of the water with respect to the ship. For a current profile the data is transformed into heading-resolved values (V_{north} and V_{east}) and averaged for a user selected period or sampling interval. A typical sampling interval for vessel mounted DCP systems is five minutes.

To calculate a velocity profile the same data set is used but no temporal averaging is performed. After each data set is sent to the processing computer the radial velocity values of the bins that were selected to be used in the calculation of the velocity profile data are statistically processed and one radial velocity value for each beam is then used in the calculation of the ship velocity with respect to the water. The statistical processing can be either a mean or median value calculation depending on the user's preference. The median value tends to have a lower standard deviation than the mean (See figures 3a and 3b) but the mean is a simpler calculation and was originally chosen to meet a processing time requirement. (Ref. 4) With today's personal computers much faster processing times can be achieved and the choice between the mean and median can be more application oriented. A comparison of figures 3a and 3b to figure 1 shows that both of the DCP methods of velocity calculation are more stable than the standard technology DSVL method.

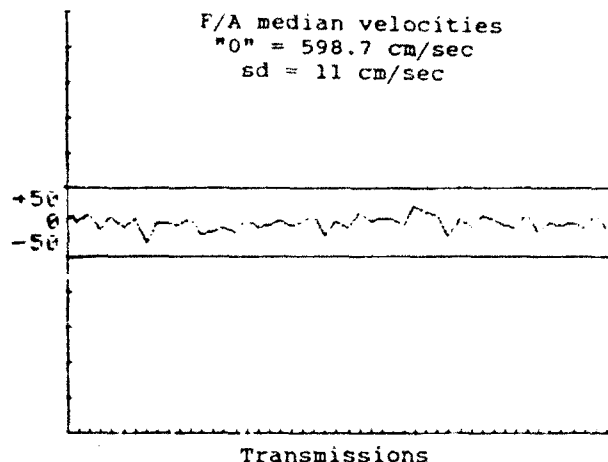
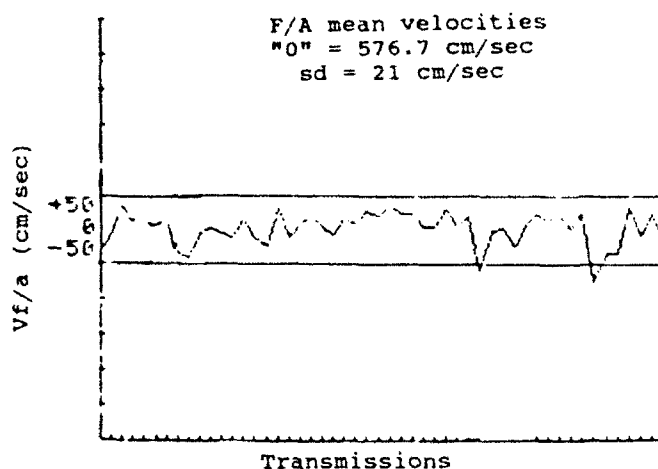


Figure 3a) DCP mean based Vf/a. (Ref. 2) Figure 3b) DCP median based Vf/a. (Ref. 2)

The selection of the bins used in the velocity profile calculation is important. The uppermost bin should be below the area of water that is displaced by ship's hull. The deepest bin used should be within an area where the returns have a strong signal-to-noise ratio.

The use of multiple depth bins to calculate ship velocity provides more stable and accurate data than single bin calculations. This is also shown by the comparison of figure 1 to figures 3a and 3b. The 115 khz DCP provides a much larger profile than is actually required for measuring ship velocity. Data taken during incremental speed runs on a US Navy test vessel were examined to see if there is any noticeable difference between velocities calculated from a 66 meter average and a 186 meter average. Single ping, time averaged, Vf/a and Vp/s were all used in the comparison. The data sets were virtually identical for both depth ranges. (See figures 4a and 4b) If a higher degree of measurement resolution is required it may be more advantageous to use a higher frequency system that will have better resolution and still attain adequate depth penetration for velocity measurement. (See table 1)

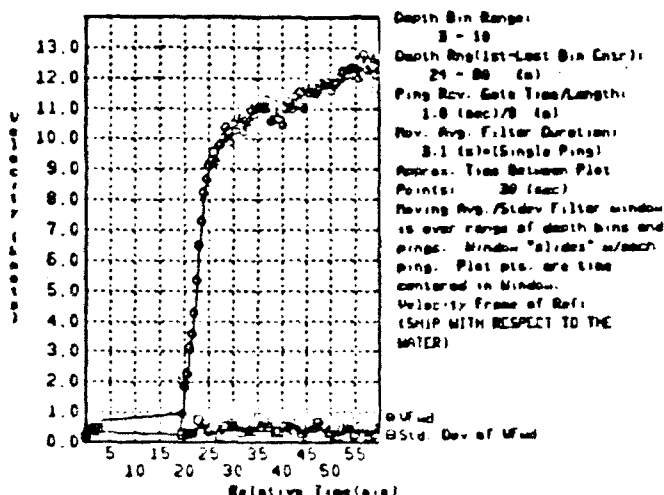


Figure 4a) DCP 66 meter based mean.

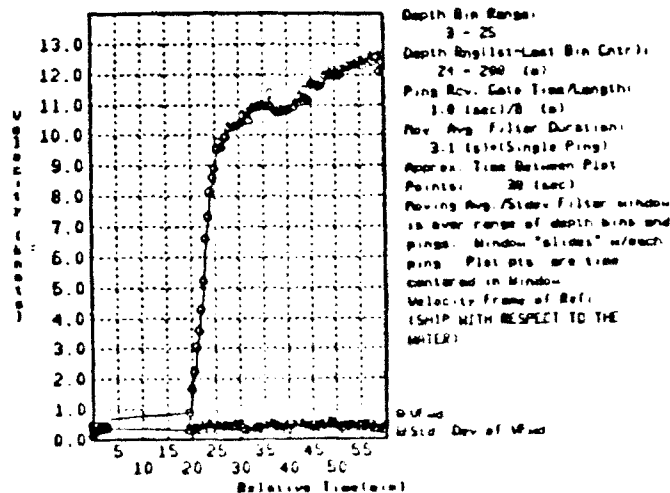


Figure 4b) DCP 186 meter based mean.

To calculate the velocity values in ship's coordinates for output to an inertial navigator or integrated navigation system the following steps are performed:

- 1) Check the validity of the selected bins of the data set.
- 2) Average the radial velocities of each beam into a single radial velocity value per beam. This is a spatial average and not temporal average. If preferred the median values could be calculated here instead of the mean values.
- 3) The velocity of the ship with respect to the water can then be calculated by inserting the four statistically processed radial velocity values into the following equations (Ref. 5):

$$V_{p/s} = K(\text{beam2} - \text{beam1}) / 2 \sin(D)$$

$$V_{f/a} = K(\text{beam3} - \text{beam4}) / 2 \sin(D)$$

$$V_{\text{vertical}} = K(\text{beam1} + \text{beam2} + \text{beam3} + \text{beam4}) / 4 \cos(D)$$

$$V_{\text{error}} = K(\text{beam1} + \text{beam2} - \text{beam3} - \text{beam4}) / 4$$

Note: The vertical velocity can be compared to the error velocity as a redundancy check to help determine the accuracy of a given data set.

Where:

$$K = -3.31337 \text{ mm/sec/count}$$

K is the scaling factor used to convert the Doppler frequency units of "counts" to mm/sec. It is negative to convert the frame of reference from the water with respect to the ship to the ship with respect to the water. This value will change with speed of sound and the transmit frequency of the system.

beam1, beam2, beam3, beam4 = The radial velocity value representing the mean Doppler shift along each of the respective beams.

D = 30 degrees the mounting angle of each transducer beam to the vertical. (See figure 5 for the transducer orientation)

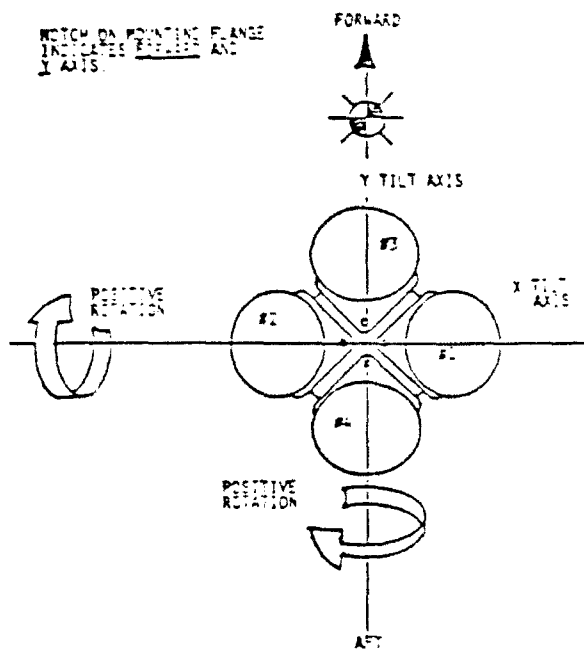


Figure 5) Orientation view from below looking up at a standard vessel mounted DCP transducer. (Ref. 5)

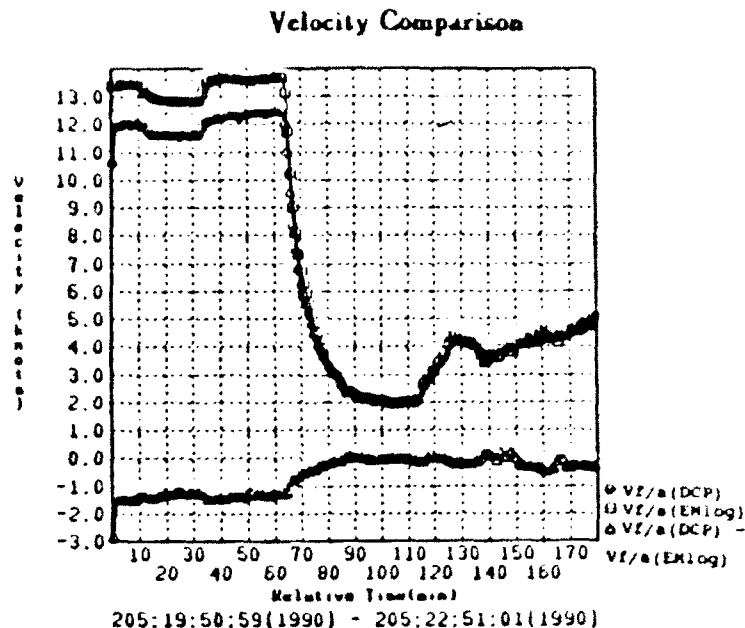


Figure 6) F/A velocity comparison between a DCP and an EMlog.

VELOCITY MEASUREMENT COMPARISONS

The DCP and EMlog are both capable of measuring the velocity of a ship with respect to the water. The EMlog measures V_f/a and the DCP measures V_f/a , V_p/s as well as the ship's vertical motion (V_{vert}). The graphs in figures 6, 7, 8a and 8b are all of the same data set. Figure 6 shows a comparison of the two systems common velocity component (V_f/a). The two systems show comparable values at the speeds below 11 knots, but have a difference of slightly greater than 1 knot at higher speeds. The DCP velocities agree with both the inertial navigator and the GPS. (See figure 7) This indicates that the EMlog is measuring a higher speed than the ship is traveling and therefore the bias is probably a result of a calibration error. This is an example of how an EMlog that measures accurately at one speed may not at another.

The DCP velocities of figure 7 are heading resolved values (V_{north}). This enables a direct comparison to the earth referenced GPS and inertial navigator systems. An inherent offset between the DCP velocity and the earth referenced velocities is caused by ocean current in the section of water that is sampled for the DCP velocity calculation. A typical value for the open seas is less than 1/2 knot. In the case of figure 7 this value appeared to be less than the resolution of

the graph. The data plotted in figures 7, 8a, and 8b is averaged over a 100 second period for each point in order to eliminate the high frequency noise associated with GPS. The difference plots in figures 8a and 8b remain close to zero throughout the speed range indicating the agreement between the DCP, GPS and inertial navigator systems.

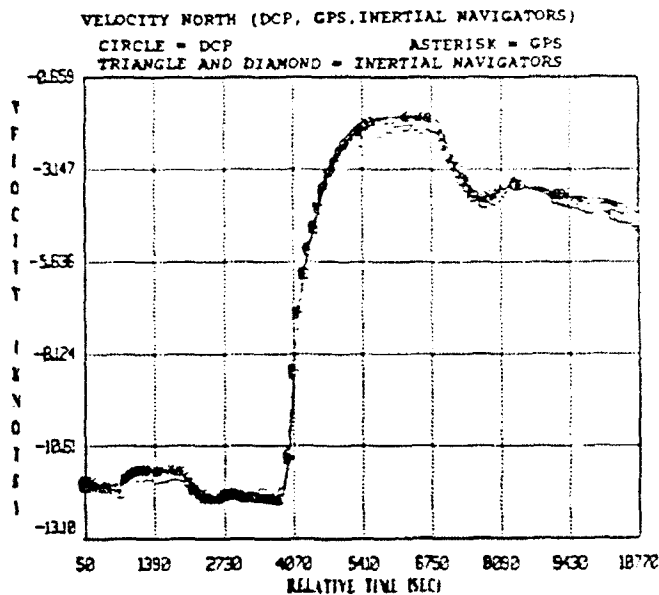


Figure 7) Velocity North comparison between a DCP, GPS and two inertial navigators.

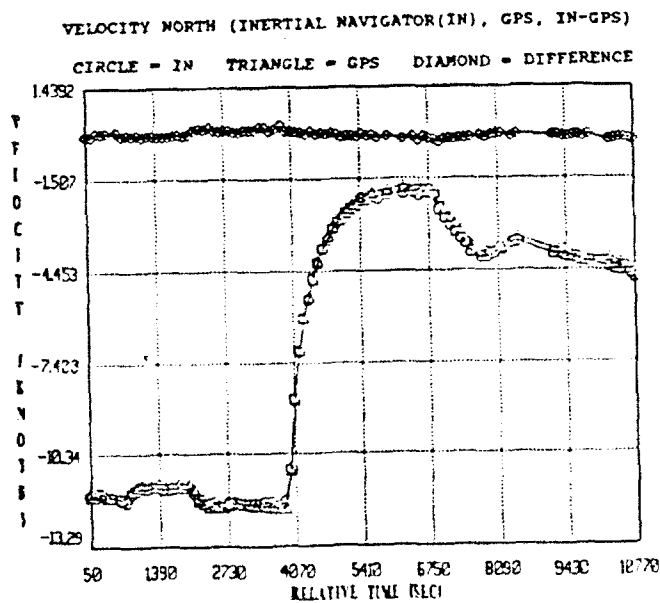


Figure 8a) Velocity North (DCP vs GPS)

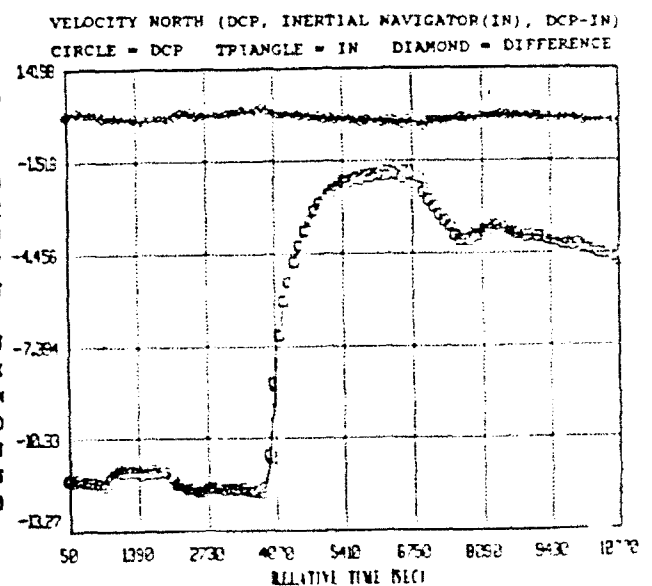


Figure 8b) Velocity North (DCP vs IN)

Figures 9a, 9b, and 9c are of the same data set. Figure 9a is a difference plot($V_f/a - V_f/a$) of the DCP and EMlog. Figure 9b is a difference plot($V_{rxy} - V_f/a$) of inertial navigator velocities transformed into ship's coordinates and of EMlog data. Figure 9c is a difference plot($V_{rxy} - V_f/a$) of the inertial navigator and the DCP. This data covers an eight hour time period in which the ship traveled in eight one hour legs of an octagon. The spurious data points of figures 9a and 9b occurred each time a course change was made demonstrating how the EMlog log can excite a Schuler oscillation during a course change. These spurious points are not evident in the difference plot of the DCP and the inertial navigator. (See figure 9c) This indicates that the DCP will not excite Schuler oscillations in an inertial navigator resulting from ship course changes.

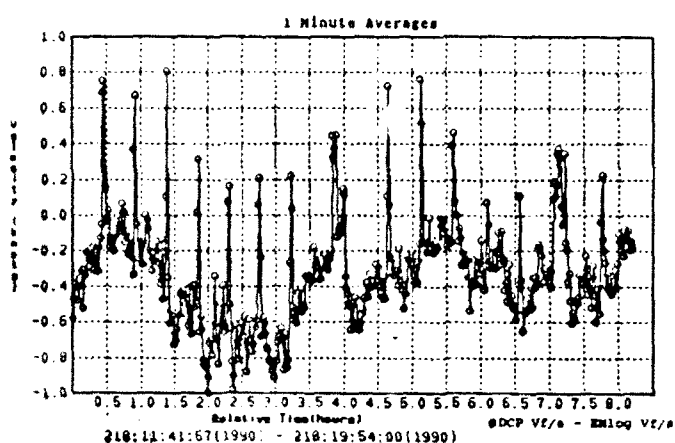


Figure 9a) Difference plot of DCP and EMlog V_f/a .

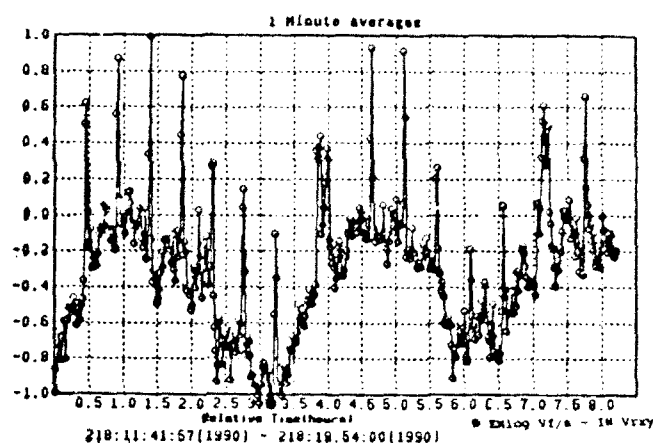


Figure 9b) Difference plot of Inertial Navigator V_{rx} and EMlog V_f/a .

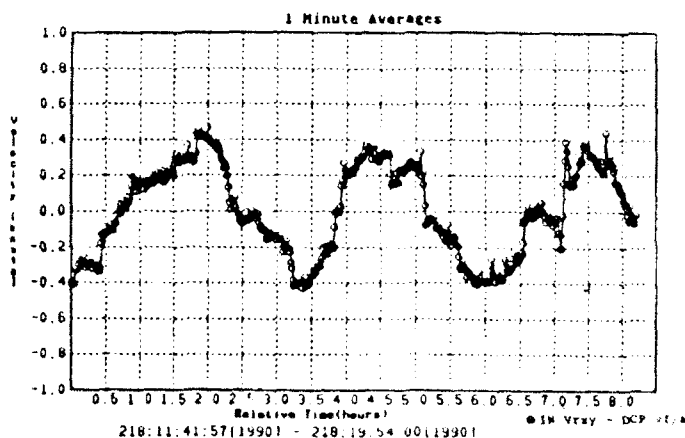


Figure 9c) Difference plot of DCP V_f/a and Inertial Navigator V_{rx} .

THE NARROWBAND DOPPLER CURRENT PROFILER ERROR MODEL

DCP errors can be classified into two groups: short-term (random fluctuations) and long-term (bias). Short-term errors can be modelled as a Gaussian zero-mean random process superimposed on a broader distribution of "outliers," occasional bad points caused by fish or severe Rayleigh fading. Outliers can be screened out using information collected by the DCP itself such as signal-to-noise level and redundancy in the vertical velocity component. The short-term errors are independent ("white noise"), except that errors in neighboring range cells have a correlation coefficient of about 13 percent and errors in sequential pings may be partially correlated if the ship velocity carries it less than about 1/2 the transducer diameter between pings. At low to moderate speeds over most of the useful depth range, the short-range rms horizontal velocity error in a single-ping measurement in one range cell is:

$$\sigma_v = \lambda c / (8\pi L \tan(30^\circ))$$

where $\lambda = c/f$ is the acoustic wavelength, c is the speed of sound, and L is the vertical length of the range cell and also the pulse. For example, a 115 kHz DCP with 8 meter range cells has rms errors $\sigma_v \approx 17$ cm/s. Profile averaging reduces the rms error by nearly the square root of the number of range cells (correlation between adjacent range cells increases the result by about 12 percent).

Thermal and ambient noise causes the short-term error to rise abruptly from the value given above when the signal-to-noise ratio drops to about 10 dB near the end of the useful depth range. At high speeds, spectral broadening proportional to the product of the beam width and the ship speed also causes the rms error to increase.

The short term error in bottom-track velocity measurements has a much smaller velocity-independent component than that of water profiles but shares the velocity-dependent component. It also tends to have somewhat more range dependence.

Long term errors can be classified as velocity-independent errors (offset bias), errors proportional to the velocity vector (scale factor bias), and other velocity dependent biases. The effect of offset bias in the velocity reference in the inertial navigator is not equivalent to that of an ocean current since it turns with the ship. Offset bias is very small (specified as ≤ 0.5 cm/s) and is attributable to filter skew and signal processing errors. Speed of sound uncertainty causes scale factor bias. Other sources of velocity-dependent bias include filter skew, thermal noise bias, beam alignment errors (both with respect to each other and to the ship's axes), and acoustic cross-coupling of adjacent beams through transducer beam pattern sidelobes. Although the velocity-dependent biases are not

strictly linear, a good approximation for calibration purposes has the form:

$$\delta U = (A + BU)[1 + C/[L(1+1/SNR)]] + (D + EU)/(1+SNR)$$

where U is the horizontal vector velocity, L is the vertical range cell size, SNR is the signal-to-noise ratio, and A, B, C, D, and E are calibration coefficients. More complex forms are possible (including cross-track bias, for example). The net scale factor bias is typically on the order of 0.2 percent.

Bottom-track biases arise from the same sources as for water profiling, except that the narrower signal bandwidth greatly reduces the filter skew effect. There are additional bias sources peculiar to bottom tracking, including terrain and absorption bias, which slightly reduce the effective beam angle to the vertical, and water bias due to near-bottom volume reverberation. Terrain and absorption bias are both scale factor biases, the latter varying linearly with altitude while the former is constant. In the ocean environment, water bias is usually negligible, rarely more than a few percent of the near-bottom current.

THE BROADBAND ACOUSTIC DOPPLER CURRENT PROFILER

The RDI Broadband ADCP is a new generation of current profiler using phase-coded pulses and advanced signal processing. Its primary advantage is reduced short-term error (by about one order of magnitude in rms velocity), allowing rapid intercalibration of DCP and inertial system errors without the need for long averaging periods. Two sources of bias, filter skew and noise bias, have been eliminated, simplifying the error model ($C=D=E=0$) and allowing the offset bias specification to be dropped to ≤ 0.2 cm/s. Although the scale factor bias specification remains at 0.2 percent, in practice Broadband ADCPs have smaller bias errors than narrowband DCPs.

A theoretical model of Broadband system performance has been developed to characterize the short-term velocity errors. Bottom velocity random errors are altitude and sonar frequency dependent as well as velocity dependent, so characterization is somewhat more complicated than for the narrowband. A first-order approximation of single-ping bottom velocity short-term error standard deviation is:

$$\sigma_b = 0.0003U + [(a + 0.003U)/(1 + bhf)](1 + 1/SNR)$$

where $a = 1$ cm/s
 $b = 0.0001$ per m-kHz
U is the ship velocity (cm/s)
H is the altitude above the bottom (m)
f is the system frequency (kHz)
SNR is the signal-to-noise power ratio

The predicted single-ping bottom velocity short-term error versus altitude is illustrated in Figure 10. Errors are shown for a 150 kHz broadband ADCP travelling at 3 m/s (6 knots). Increases in errors at higher frequencies are due to lower SNRs occurring there. Errors also increase at low altitudes because the number of independent samples available from bottom echoes decreases at low altitudes, and because of signal processing approximations. Over the mid-altitude range, broadband errors are about an order of magnitude less than for narrowband DCPs.

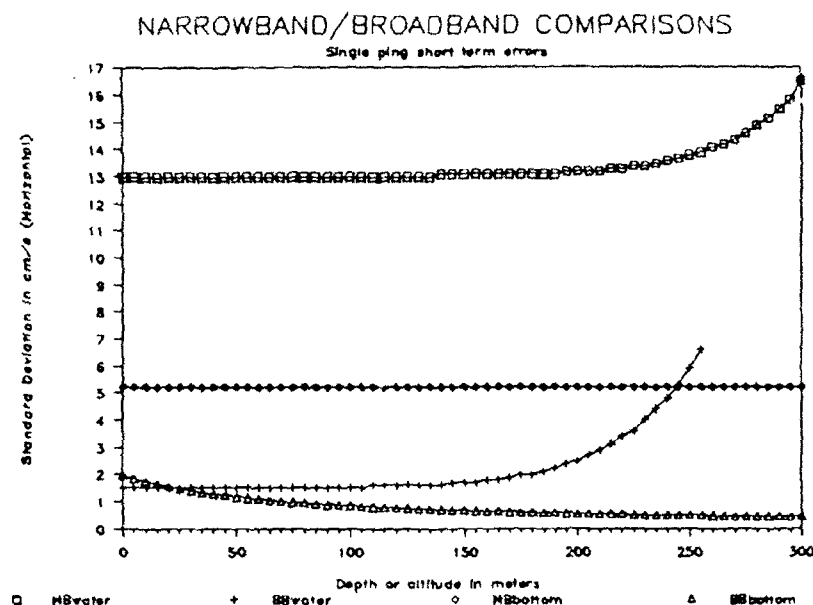


Figure 10) Predicted single-ping short-term error versus altitude.

Broadband water velocity random errors primarily depend upon the sonar frequency and range cell size. A first-order approximation of single-ping horizontal water velocity short-term errors is of the form

$$\sigma_v = (0.002U + a/Lf)(1 + 1/\text{SNR})$$

where $a = 3000 \text{ (cm/s) - m - kHz}$

L is the range cell size in vertical meters

For a typical Broadband 150 kHz ADCP with 8 meter range cells at a 3 m/s (6 knot) velocity, the single ping water velocity standard deviation is about 3 cm/s. This is also about an order of magnitude less than for a narrowband DCP. Hence averaging periods and filter time constants can be roughly two orders of magnitude shorter with the Broadband ADCP and have about the same residual error level as the narrowband system.

Summary

The technique of accurately measuring ship speed with respect to the water by statistically processing the multibin vertical water column profiles of the Doppler Current Profiler has been tried and proven to be viable and more reliable than the traditionally used methods. The velocity values are stable and calculated from samples taken from areas not subject to the hull displacement errors that affect the Electromagnetic Log.

The DCP can be used to supply damping velocities to an integrated navigation system and simultaneously collect ocean current profile data. The DCP can bottom track to 700 meters, eliminating ocean current errors.

The next generation current profiler, the Broadband Acoustic Doppler Current Profiler, provides the advantage of a reduced velocity variance and finer depth resolution over existing current profilers which can only improve the velocity logging and ocean current measurement capabilities of current profiling systems.

Biographies

Peter T. Shaw is an electronics engineer in the Sonar Systems Development Branch of the Precision Navigation Systems Division at NRaD-Warminster, PA. During his tenure at NRaD-Warminster he has worked with Doppler sonar based systems and the ocean bottom mapping Sonarray Survey System. He received his B.S. degree from Temple University in 1983.

Blair H. Brumley received the Sc.B. degree from Brown University, Providence, RI in 1975, and the M.S. and Ph.D. degrees from Cornell University, Ithaca, NY in 1979 and 1984, respectively; all three degrees were in environmental engineering. Since 1989 he has been a Research Scientist at RD Instruments, San Diego, CA. He spent the previous five years with the Applied Ocean Physics and Engineering Department at the Woods Hole Oceanographic Institution as a Postdoctoral Investigator, Postdoctoral Scholar, and Assistant Scientist. His research interests include turbulence, sediment transport, gas transfer, bubbles, high-frequency acoustics, and signal processing.

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